ACOUSTICAL CHARACTERISTICS
OF OIL PALM MESOCARP FIBRES

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"Special dedicated to my beloved parent and my sibling who always gave me support and encouragement"

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ABSTRACT

Natural fibres are availability biomass, plentiful in agricultural waste and eco-friendly materials. Currently, it is become the major reasons for emerging renewable materials in sustainable technology. Therefore, this study discusses the acoustical characteristics of agro-waste biomass fibres from oil palm *Mesocarp* as fibrous acoustic material. Incorporated polyurethane (PU) had improved the sound absorption coefficient (SAC), especially at low frequency range. The oil palm *Mesocarp* fibres were mixed with four different percentages of PU, namely 10%, 20%, 30% and 40%. The measurement of SAC was done using an impedance tube method (ITM). Moreover, there were two analytical models which are Delany-Bazley model and Johnson-Champoux-Allard model to validate the experimental outcomes. There were several internal characteristics of the prepared samples investigated namely flow resistivity, porosity, tortuosity, characteristic lengths, fibre diameter, air gaps and thickness of sample. The flow resistivity, tortuosity, fibre diameter, density of samples and characteristic lengths tend to increase with percentage of PU binder. But, porosity was slightly decrease by adding more binder into the sample. This study confirms that by increasing the thickness of samples, the SAC were improved. Air gaps had great influence in adjusting amount of low frequency range and moved the peaks toward lower frequency. The internal characteristics have a positive and significant effect on Noise Reduction Coefficient (NRC). The sample with 10% PU binder showed the greatest sound absorption performance in most of low to mid frequency range and demonstrated highest value of NRC of 0.66. Besides, sample with 20% PU binder demonstrated optimum SAC which is very close to 1 at 1000 Hz. There is still space to improve the performance of the Delany-Bazley Model, especially for natural fibre. Besides, the Johnson-Champoux-Allard model gives similar pattern of graph to ITM results and the model predicts very well with better fit to acoustic behaviour.

ABSTRAK

Serat semula jadi adalah biomass ketersediaan, banyak di sisa pertanian, dan bahan mesra alam. Pada masa kini, ia telah menjadi sebab utama penghasilkan bahan-bahan yang boleh diperbaharui dalam teknologi mampan. Lantaran itu, kajian ini membincangkan ciri-ciri akustik serat biomass agro-buangan dari *Mesokap* kelapa sawit sebagai bahan akustik berserat. Hasil dari gabungan pengikat *Polyurethane* (*PU*) telah meningkatkan pekali penyerapan bunyi (SAC), terumatanya pada julat frekuensi rendah. Serat *Mesokap* kelapa sawit diadun dengan empat peratusan pengikat PU yang beza-beza, iaitu 10%, 20%, 30% dan 40%. Pengiraan SAC telah dilakukan dengan menggunakan tiub galangan (ITM). Tambahan pula, terdapat dua model analisis seperti model Delany-Bazley dan Johnson-Champoux-Allard dijalankan untuk mengesahkan keputusan yang diperolehi dari ITM. Terdapat beberapa ciri dalaman sampel yang telah dianalisis antaranya kerintangan aliran, keliangan, kedalaman keliangan, bentuk keliangan, diameter serat, ruang udara dan ketebalan sampel. Kerintangan aliran, kedalaman keliangan, diameter serat, ketumpatan dan bentuk keliangan cenderung untuk meningkat dengan peratus pengikat. Tetapi, keliangan sedikit berkurang dengan penambahan lebih banyak pengikat ke dalam sampel. Kajian ini mengesahkan bahawa penambahan ketebalan sampel dapat memperbaiki SAC. Ruang udara dibelakang sampel mempengaruhi sejumlah julat difrekuensi rendah dan mengalih puncak ke arah frequency lebih rendah. Sampel dengan 10% pengikat menunjukkan prestasi penyerapan bunyi yang baik dalam lingkungan frequensi rendah dan memiliki nilai pekali pengurangan bunyi (NRC) iaitu 0.66. Selain itu, sampel dengan 20% pengikat menunjukkan SAC optimum yang mana amat hampir dengan 1 di 1000 Hz. Masih terdapat ruang untuk meningkatkan prestasi model Delany-Bazley terutamanya untuk serat asli. Selain itu, model Johnson-Champoux-Allard menunjukkan bentuk seakan dengan graf ITM dan model ini boleh meramal dengan padanan yang lebih sesuai kepada ciri-ciri akustik.

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LIST OF SYMBOLS

H_Z	-	Hertz
dB	-	Decibels
λ	-	Wavelength
v	-	Velocity of sound, air velocity
f	-	Frequency
R_1	-	Specific flow resistance
u	-	Particle velocity through sample
Δp	-	Sound pressure differential across the thickness of the sample measured in direction of particle velocity
ΔT	-	Incremental thickness
P	-	Static pressure differential between both faces of the sample, power incident, power transmitted
l	-	Thickness of sample, total length of fibre
ε	-	Porosity
V_a	-	Volume of the air in the voids
V_m	-	Total volume of the sample of the acoustical material being tested
k_s	-	Tortuosity
L_e	-	Effective channel length or effective sample thickness
L	-	Thickness of the sample
α	-	Sound absorption coefficient
I_i	-	Incident sound energy
I_a	-	Sound absorbed
τ	-	Sound transmission coefficient
T	-	Reverberation time

V	-	Volume of the room
A	-	Total absorption, total area of the object
ρ_A	-	Average area density
m	-	Total mass of the object
W_w	-	Weight wet
W_d	-	Weight dry
W_f	-	Weight float
W_s	-	Weight of sample (saturated)
W_d	-	Weight of the sample (dry)
W_i	-	Weight of sample immersed (saturated)
Z_c	-	Characteristic of impedance
k	-	Wave-number, complex wave-number
ρ_0	-	Density of air
c_0	-	Speed in air
ω	-	Angular frequency
σ	-	Flow resistivity
C_{eq}	-	Frequency dependent sound speed
ρ_{eq}	-	Density of a highly porous material
ρ_e	-	Effective density
ρ_s	-	Density of saturating liquid
K_e	-	Effective bulk modulus of the air
γ	-	Air as the ratio of specific heat
P_0	-	Atmosphere pressure
η	-	Viscosity of air
N_p	-	Prandtl number
δ_v	-	Thickness size of viscous
δ_h	-	Thermal boundary layer
c_p	-	Specific heat capacity of air at constant pressure
V_p	-	Pore volume
V_b	-	Bulk volume
Λ	-	Viscous characteristic length
Λ'	-	Thermal characteristic length

LIST OF ABBREVIATIONS

NRC	-	Noise reduction coefficient
STL	-	Sound transmission loss
SAC	-	Sound absorption coefficient
NRI	-	Noise Reduction Index
ITM	-	Impedance Tube Method
PU	-	Polyurethane
ISO	-	International Organization for Standardization
ASTM	-	American Society for Testing and Materials
UTHM	-	Universiti Tun Hussein Onn Malaysia
MPOB	-	Malaysian Palm Oil Board
FRIM	-	Forest Research Institute Malaysia
Pa	-	Pascal
M1	-	Microphone 1
M2	-	Microphone 2
MATLAB	-	Matrix Laboratory
Sdn	-	Sendirian
Bhd	-	Berhad

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Over the past centuries, great efforts have been made to investigate sound absorption panel. Over this time, the focus of attention is on the use of material in making sound absorption panel. Most absorption panels used for sound absorption that available in the market at present are a variety of traditional synthetic fibres such as glass wool, rock wool, and asbestos, because of their high performance at mid-high frequency range. Moreover, these materials offer outstanding thermal and absorption properties, unique flexibility in design capabilities, and ease of fabrication. Despite its efficacy, the synthetic fibres produced several major drawbacks. Since 40 years ago, the European Council Directive has stated that the synthetic fibre has several disadvantages where the fibre can lay down in the lung alveoli and cause skin itching (Council Directive, 1967). According to Rapisarda *et al*., (2015), they found that the synthetic fibres exposure significantly to the human related to increased oxidative.

Due to the environmental concerns, there are a lot of needs and demands to find replacement or renewable materials in the making of acoustical panel. There was an increasing interest in green technology, which is to replace the synthetic fibre with agrowaste and agroforest materials. Moreover, natural fibres are being used in many products such as automotive industry, interior lining for apartments, aircrafts, ducts and biocomposite products (Chandramohan & Marimuthu, 2011).

The utilization of natural fibres has drawn attentions many researchers due to the environmental pollution, reduction of waste disposal problems (Nishino, Matsuda, & Hirao, 2004) and their low density, biodegradable, and low cost (Zhu *et al*., 2013).

Normally, porous materials are often used in absorbing sound. A porous material means a material that contains many voids and not be interconnected. The material contains a solid matrix that is connected, so that it can resist shear stresses, and within which are small pores filled with a compressible fluid (Rossing & Beranek, 2009). The porous absorber will reduce the speed of sound and consequently a given thickness of absorber will improve the lower frequency. In order to understand the theoretical model of sound propagation through a porous material, it is necessary to set down the measurement characterizing which determining the acoustic behaviour of sound within porous absorbents. There are two basic material characteristics within porous absorbents, namely flow resistivity and porosity. The flow resistivity and porosity are usually the most important parameters for determining the material characteristic (Cox & D'Antonio, 2010). These parameters can change the absorption behaviour (Seddeq, 2009).

In recent decades, new ways to predict and measure absorptive materials have been developed. A commonly used model in the prediction of waves in porous media was developed by Biot (1956a). This model was based on the Hamilton's principle. A widely and simple model which involves a single parameters (flow resistivity) for the acoustical properties was developed by Delany & Bazley (1970). It is also possible to predict the characteristic impedance by considering the microscopic propagation within the pores when given the material properties; flow resistivity, porosity, tortuosity and characteristic lengths. This simple phenomenological model has been developed by many of people in the development of the models (Allard & Atalla, 2009; Attenborough, 1971; Champoux & Allard, 1991; Johnson, Koplik, & Dashen, 1987). In order to gain an accurate prediction of the sound characteristic is problematic, and consequently it is necessary to have the comparison between theoretical and experimental results.

1.2 Problem Statement

Regarding to environmental and sustainability concerns, a great effort has been made to produce a product-based on the green materials, especially in the acoustical panel. This is because, normally a commercial products are made from man-made vitreous fibres refers to a group of synthetic fibre including glass wool, rock wool, slag wool and asbestos. Unfortunately, these materials known to be hazardous to our health and also contribute higher to Global Warming Potential (GWp) kg CO_2 (Asdrubali, 2006). Approximately, 27% of mineral wool (glass), 30% of mineral wool (stone) and 40% of foam plastic has been estimated in European building insulation (Schmidt *et al*., 2004). A number of epidemiological studies have found an increased risk of human respiratory system cancer when man-made fibre exposed to workers (Berrigan, 2002; Marsh *et al*., 2001; Stone *et al*., 2004).

Since in 1987, the definition of sustainability was developed by the World Commission on Environmental and Development which became widely known as the Brundtland Report. "*Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs"*, was stated in that report (Brundtland, 1987). However, sustainability is still a relatively new concept in many developing countries that are heading toward industrialization, including Malaysia. The implementation of the sustainability concept in Malaysia is still in early stage (Abidin, 2010). Implementing sustainable development becomes problematic due to lack of sustainable materials, method and technologies (Shafii *et al*., 2006). Thus, in order to implement sustainability, a strong financial supports and aids are needed due to the cost is often higher than anticipated.

Natural fibres can be considered as a good potential to replace the synthetic fibres and to implement the sustainability materials. However, most of the natural fibres in the country are left abandoned. Approximately 22% of fibres produced from palm oil industry have been wasted (Badri *et al*., 2005). Over the last decade, the increasing demands on palm oil have made Malaysia as a major player in the world's oil palm industry. As of 2011, there are about 57% of total production occurs in West Malaysia and 99% in Sabah and about 5 million hectares of area palm oil has been planted (Malaysia Palm Oil Board, 2011). Thus, this has largely contributed to abundant source of biomass materials. Forest Research Institute of Malaysia (FRIM) and Malaysia Palm Oil Board (MPOB) have conducted fundamental research for many years to find the potential use of palm oil residues as raw materials for various products. Raw materials obtained from palm oil trees have been used widely in biomass media, mattress, fibre board, cushion, rugs, carpets and rope manufacturing. Unfortunately, there is a lack of scientific information on acoustical characteristic of oil palm *Mesocarp* fibres. Hence, the purpose of this research is to investigate the potential of oil palm *Mesocarp* fibres on acoustical performance.

1.3 Research Questions

There are some important questions based on the discussion above. These questions are:

1. Are oil palm *Mesocarp* panels feasible to be applied for acoustical panels?
2. If so, what are the acoustical characteristics of the oil palm *Mesocarp* panels?
3. What are the physical characteristics and how it is influencing on acoustical characteristics?
4. How can analytical models support the results of acoustical properties of oil palm *Mesocarp* panels?

1.4 Research Objectives

The objectives of the study are:

1. To determine the acoustical characteristics of oil palm *Mesocarp* panels.
2. To determine the physical properties of oil palm *Mesocarp* panels.
3. To investigate the effects of physical characteristics, air gap and thickness on acoustical characteristics of oil palm *Mesocarp* panels.
4. To determine the acoustical characteristics of oil palm *Mesocarp* panels using analytical models.

1.5 Scope of Research

The scope of the study is limited to:

1. The acoustical panels are made from oil palm *Mesocarp* natural fibre and mixed with Polyurethane (PU) as a binder.
2. Four percentages of binder which are 10%, 20%, 30% and 40%.
3. The parameters implemented in this study such as flow resistivity, porosity, tortuosity, characteristic lengths, density, fibre diameter, air gap and thickness.
4. The acoustical characteristics are sound absorption coefficient (SAC) and noise reduction coefficient (NRC) which is carried out experimentally.
5. Two analytical models involved which are Delany-Bazley Model and Johnson-Champoux-Allard Model which is carried out analytically.

1.6 Organization of the Thesis

This section provided a brief summary of the thesis organization. There are five chapters were organized in this thesis. This thesis first gives an overview of the background, problem statement, research questions, objectives and scope of research.

Chapter 2 begins by laying out the comprehensive literature review about the acoustical characteristic, natural fibres and related parameters outcomes. The theoretical models about an equivalent fluid model of porous absorbent are also explicated.

Chapter 3 describes the research methodology, including material preparation, sample preparation, all parameters and impedance tube method setup. A depth explanation about the equivalent fluid model of porous absorbents measurement is also presented in this chapter.

Chapter 4 discusses the experimental results and the analytical predictions of equivalent fluid model of porous absorbent. The influences of physical characteristic are presented in this chapter.

Finally, Chapter 5 highlights and summarizes the results of the research and provides some further works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Acoustics

The word “acoustic” is comes from the Greek word *akouein* which means to hear (Lindsay & Shankland, 1973). Rossing & Beranek (2009) defined acoustic as the science of sound that deals with the development of sound, the propagation of sound and the detection and perception of sound. They also described acoustic as the interdisciplinary science, involving the study of physics, engineering, physiology, speech, audiology, music, architecture, physiology, and neuroscience. Bies & Hansen (2009) stated that acoustic field is the study of small pressure fluctuations in the air. Acoustic or sound can be defined as a movement of wave in air or other medium such as the excitation of the hearing mechanism that results in the perception of sound (Everest & Pohlmann, 2001). The acoustics is the field that deals, in the broadest sense, with the interaction of sound fields or mechanical vibratory phenomena with organisms (Rosenblith & Stevens, 1953). In the acoustic field, various definitions of acoustic are found. Although, there are several definitions defined by acousticians, these definitions actually describes the same meaning but with different view and concept.

The acoustic also overlaps with law of physics. There are several fundamentals and studies that included in the physics of acoustic and produced a change of acoustical properties which is sound wave phenomena, transmission, reflection, absorption, refraction, dispersion, interference, diffraction and scattering.

The term “sound” is used to describe auditory sensation in the ear and disturbance in a medium that can cause this sensation. Vibrating bodies, changing airflow, time-dependent heat sources and supersonic flow are the processes that can produce sound (Rossing & Beranek, 2009). Sound waves propagate and travel through the surrounding medium; gases, liquids and solids. Thus, without medium, sound cannot propagate. Sound also can be categorized into different types which include, the sound that can be detected by ear, ultrasound (sound waves with frequency above the range of human hearing; >4000Hz) and infrasound (sound waves below the frequency of human hearing; <4000Hz), environmentally (likes bird, dog and waterfall) sound, and aesthetic sound (music). The minimum sound pressure audible that can be detected by a young human is approximately 20×10^{-6} Pa or 2×10^{-10} atmospheres (1 atmosphere equals 101.3×10^{3}). For a normal human ear, it can be considered painful when the sound pressure is 6×10^{-4} atmospheres (Bies & Hansen, 2009).

Generally, there are three characteristics used to visualize a sound wave; amplitude, frequency and wavelength. Frequency is defined as properties of periodic waves and it is measured in $Hertz$. Amplitude is a measurement of the amount of energy travelled in the wave. Wavelength is the distance of sound propagation in the one cycle with certain time. A wavelength can be determined from a point of phase to another point on the next phase (Bies & Hansen, 2009). Frequency and wavelength can be expressed as illustrated in equation 2.1 and 2.2.

$$Wavelength = \frac{Speed\ of\ sound}{Frequency} \tag{2.1}$$

or can be written as:

$$Frequency = \frac{Speed\ of\ sound}{Wavelength} \tag{2.2}$$

Normally, equation 2.1 and 2.2 is used frequently in the field of acoustic. Figure 2.1 shows the illustration of wavelength and peak amplitude.

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